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USING PHOTOTHERMAL DEFLECTION TECHNIQUES FOR STUDYING THE ATTENUATIONS OF GUIDED WAVES PROPAGATED IN OPTICAL THIN FILMS

by

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USING PHOTOTHERMAL DEFLECTION TECHNIQUES FOR STUDYING THE ATTENUATIONS OF GUIDED WAVES PROPAGATED IN OPTICAL THIN FILMS

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Liu Xu

ABSTRACT

A new experimental system, utilizing photothermal deflection techniques, does test measurements of guided wave propagation attenuation in optical thin films. Lessons are drawn from propagation attenuation in wave guidance optics in order to characterize the losses and qualities associated with high quality optical thin films. Experimental results clearly show that attenuation coefficients are capable of very sensitively and completely reflecting thin film properties and quality.

I. INTRODUCTION

Following along with expansions in the realms of optical thin film applications, there is a requirement to prepare thin film samples with extremely high performance. Moreover, improvements in thin film technology and perfecting of industrial techniques make their preparation become possible. This then forces a necessity for means and methods to be able to sensitively and accurately check weak losses. Traditional optical thin film test measurement methods--because of limitations associated with thin film thicknesses--had very greatly limited sensitivities and ranges which could be surveyed. As far as modern developments in optronic technology are concerned, light wave guide sample performance has rapidly risen. At the present time, light wave guide sample losses will be smaller than optical thin films by several orders of magnitude, close to the performance of block materials. These impel our consideration of whether or not it is possible to borrow for use

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

methods for precisely specifying losses in light wave guides in order to study loss characteristics of high quality optical thin films.

In wave guide optics, guided wave propagation attenuation is used to characterize thin film performance and quality. Due to the fact that guided waves--during propagation in thin film wave guides--have relatively long action distances from thin film media, as a result, guided wave propagation attenuation is capable of sensitively and fully reflecting thin film loss information [1]. With that the case, using propagation attenuation in order to study or characterize high quality optical thin film loss characteristics is superior. At the same time, it comprehensively reflects the two basic types of optical thin film losses: absorption and scattering losses.

Photothermal deflection techniques are methods which appeared in the 1980's and are used in accurately checking material thermal parameters as well as weak absorption [2]. Measured samples absorb irradiated light from modulation pumps and produce areas of rising temperature. Caused by thermal expansion, gradient distributions associated with refraction indices of samples and surrounding media are given rise to. These refraction gradients will cause another survey light beam passing through media to produce deflections. Surveying the deflection angle of this beam, it is then possible to invert to get the absorption or thermal parameters associated with the material. Photothermal deflection techniques possess very high degrees of sensitivity to absorption.

This article will use these techniques to study guided wave propagation in optical thin films. In conjunction with this, guided wave propagation attenuation will be used in order to characterize the size of thin film losses.

II. EXPERIMENTAL PRINCIPLES

Fig.1 is the experimental system to take photothermal deflection techniques and use them on thin film guided wave propagation. Going through a coupling prism, the pump laser beam is coupled into the wave guide thin film. The guided wave light propagates along the direction z. However, the survey light beam penetrates various types of sample and air media vertically. With this type of situation being the case, the temperature effects in each medium all produce influences on the survey light beam.

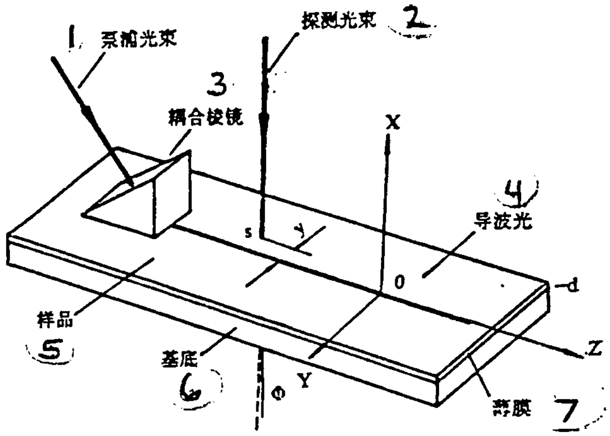

Fig.1 Photothermal Deflection Technique Experimental System and Coordinate Set Up

Key: (1) Pump Light Beam (2) Survey Light Beam (3) Coupling Prism (4) Guided Wave Light (5) Sample (6) Base (7) Thin Film

In the experimental system, due to thin film absorption of guided wave light, one has the production of temperature changes on the sample periphery. Assuming one takes guided waves of a certain guided mode associated with frequency ω modulation, and they propagate along direction oz in a thin film, the guided wave light--in the Y direction--presents a Gauss function

distribution. In wave guides, only thin film media show the existence of absorption. On the path of this type of guided wave propagation, there is absorption at locations S(y,z) within unit elements. In conjunction with this, modulation energy densities transformed into quantities of heat are:

$$Q(y,z)=\frac{\Gamma_0 P e^{-y^2/2a}}{2ad}e^{i\omega t} \tag{1}$$

In the equation, 2a is the Gauss beam width. Γ_0 is the absorption coefficient. P is the pump light energy in the thin film at location S. d is the thin film thickness. Here, we ignore changes in heat density along direction z within unit elements. The reason for this is that the survey light beam is focused. The S point is very small.

Taking heat propagation equations and applying them to the various types of media associated with the Fig.1 system as well as giving consideration to temperature functions T, which are the same for modulation frequencies ω , one has [2]:

$$\begin{cases} \frac{\partial^2 T_c(x,y)}{\partial x^2}+\frac{\partial^2 T_c(x,y)}{\partial y^2}-\frac{i\omega}{K_c}T_c(x,y)=0 & x\geqslant 0 \quad \text{air} \\ \frac{\partial^2 T_f(x,y)}{\partial x^2}+\frac{\partial^2 T_f(x,y)}{\partial y^2}-\frac{i\omega}{K_f}T_f(x,y)=-\frac{Q}{k_f} & -d\leqslant x\leqslant 0 \quad \text{thin film} \\ \frac{\partial^2 T_s(x,y)}{\partial x^2}+\frac{\partial^2 T_s(x,y)}{\partial y^2}-\frac{i\omega}{K_s}T_s(x,y)=0 & x\leqslant -d \quad \text{base} \end{cases} \tag{2}$$

In these, T_i are, respectively, temperature coefficients associated with media i (i=c,f,s). $K_i=k_i/\rho_i c_i$ is the thermal diffusion coefficient associated with medium i. ρ_i, c_i, and k_i are, respectively, density, thermal capacity, and thermal conductance coefficients associated with corresponding media. Besides this, corresponding thermal propagation boundary conditions are:

$$T_c(0,y)=T_f(0,y) \quad \text{while} \quad k_c\frac{\partial T_c}{\partial x}\bigg|_{x=0}=k_f\frac{\partial T_f}{\partial x}\bigg|_{x=0}$$

$$T_f(-d,y)=T_s(-d,y) \quad \text{while} \quad k_f\frac{\partial T_f}{\partial x}\bigg|_{x=-d}=k_f\frac{\partial T_s}{\partial x}\bigg|_{x=-d}$$

In order to solve thermal propagation equation set (2), take temperature function $T_i(x,y)$ and source $Q(y)$ to make a Fourier transform for variable y, noting $\tilde{T}_i(x,\xi)$ and $\tilde{Q}(\xi)$. Considering thermal diffusion physics processes, it is possible to extrapolate to temperature distributions for various media:

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$$\begin{cases} \tilde{T}_s(x,\xi) = A(\xi)e^{-\sigma_s x} \\ \tilde{T}_f(x,\xi) = B(\xi)e^{-\sigma_f x} + C(\xi)e^{\sigma_f x} + 0(\xi) \\ \tilde{T}_c(x,\xi) = D(\xi)e^{-\sigma_c(x+d)} \end{cases} \tag{3}$$

In the equations,

$$\sigma_i = \left(\xi^2 + \frac{i\omega}{K_i}\right)^{\frac{1}{2}}, \quad 0(\xi) = \frac{\Gamma_0\sqrt{\pi}\,P}{2\sqrt{2}\,d\sigma_f^2 k_f} e^{-\frac{\xi^2 a^2}{8}}$$

$$A(\xi) = \left[\frac{2\sigma_f k_f \sigma_s k_s - \sigma_c k_c\{(\sigma_s k_s - \sigma_f k_f)e^{-\sigma_f d} - (\sigma_s k_s + \sigma_f k_f)e^{\sigma_f d}\}}{\Delta} + 1\right]0(\xi)$$

$$B(\xi) = \left[\frac{\sigma_s k_s(\sigma_c k_c + \sigma_f k_f) - \sigma_c k_c(\sigma_s k_s - \sigma_f k_f)e^{-\sigma_f d}}{\Delta}\right]0(\xi)$$

$$C(\xi) = \left[\frac{\sigma_c k_c(\sigma_s k_s + \sigma_f k_f)e^{\sigma_f d} - \sigma_s k_s(\sigma_c k_c - \sigma_f k_f)}{\Delta}\right]0(\xi)$$

$$D(\xi) = \left[\frac{2\sigma_f k_f \sigma_c k_c + \sigma_s k_s\{(\sigma_c k_c + \sigma_f k_f)e^{\sigma_f d} - (\sigma_c k_c - \sigma_f k_f)e^{-\sigma_f d}}{\Delta} + 1\right]0(\xi)$$

$$\Delta = (\sigma_c k_c - \sigma_f k_f)(\sigma_s k_s - \sigma_f k_f)e^{-\sigma_f d} - (\sigma_s k_s + \sigma_f k_f)(\sigma_c k_c + \sigma_f k_f)e^{\sigma_f d}$$

because of this, thin film wave guide sample temperature distribution functions in three types of media are then the inverse Fourier transforms associated with corresponding functions in equations (3).

Spacial temperature distributions given rise to by thin film absorption will produce corresponding spacial distributions associated with refraction indices. The reason for this is that media refraction indices are functions of temperature. When a probe survey beam penetrates the nonuniform media described above, the beam locus satisfies [2]:

$$\frac{d}{ds}\left(n_0\frac{\partial \vec{r}_0}{\partial \tau}\right) = \nabla_\perp n(r) \tag{4}$$

In this, τ is the original beam propagation locus. $\vec{r}_0$ is the vertical displacement of the original propagation direction. $\nabla_{\perp}n(r)$ is the refraction index gradient perpendicular to direction τ. According to the coordinate set up in Fig.1, considering the fact that survey beam photothermal deflection angles are extremely small, it is possible to get deflection angles to be :

$$\phi(y) \cong \frac{d\vec{r}_0}{d\tau} = \sum_{i=c,f,s} \frac{1}{n_i}\frac{\partial n_i}{\partial T}\int_{\text{path}} \frac{\partial T_i}{\partial y}dx \qquad (5)$$

In the equation, $\frac{\partial n_i}{\partial T}$ is the refraction temperature coefficient associated with medium i. Substituting temperature distribution functions associated with various media and applying Fourier transform properties, it is possible to obtain:

$$\begin{aligned}\phi(y) = \frac{1}{2\pi}\Bigg\{&\frac{1}{n_c}\frac{\partial n_c}{\partial T}\int_{-\infty}^{+\infty}\frac{i\xi A(\xi)}{\sigma_c}e^{i\xi y}d\xi + \frac{1}{n_s}\frac{\partial n_s}{\partial T}\int_{-\infty}^{+\infty}\frac{i\xi D(\xi)}{\sigma_s}e^{i\xi y}d\xi \\ &+\frac{1}{n_f}\frac{\partial n_f}{\partial T}\int_{-\infty}^{+\infty}\left(\frac{B(\xi)[e^{\sigma_f d}-1]}{\sigma_f}+\frac{C(\xi)[1-e^{-\sigma_f d}]}{\sigma_f}\right. \\ &\left.+\,0(\xi)d\right)e^{i\xi y}d\xi\Bigg\}\end{aligned} \qquad (6)$$

Due to the fact that factors $A(\xi)$, $B(\xi)$, $C(\xi)$, $D(\xi)$ and $0(\xi)$ in the equations all form direct proportions with the pump light strength P at location S in thin films, deflection angles $\phi(y)$, therefore, also form direct proportions with guided light strengths at location S. Variable y represents the center distance of survey light beams and pump light beams (Fig.1). Because of this, changes in photothermal signals along the direction oz are then capable of representing guided wave light strength changes following along with propagation distances. /236

Fig.2 gives theoretical calculation results for photothermal signals and the distances y between two light beams. Basic characteristics of photothermal signals are: when survey beams

penetrate pump light centers (y=0), photothermal signals tend toward zero. However, on the two sides of pump light centers, there is a maximum value location on each one. They each correspond to temperature gradient maximum value locations. With this the case, it is possible to use them in order to characterize pump light beam widths. More detailed theoretical analysis clearly shows that, following modulation frequency rises, photothermal signals get weaker. During experiments, therefore, one should rationally select pump light frequencies to make signals not become too weak. At the same time, the influence of noise cannot be too great.

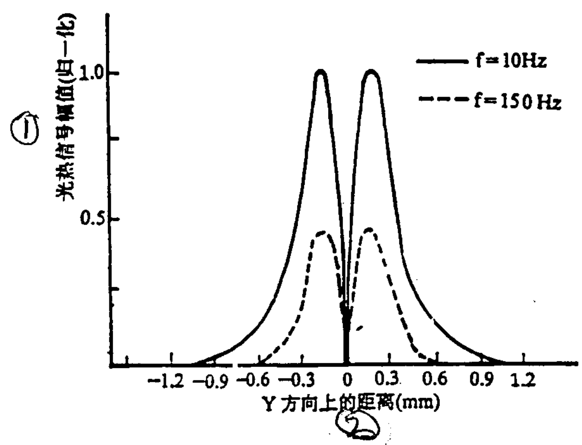

Fig.2 Relationships Between Photothermal Signal Peak Values and Two Light Beam Distances y

Key: (1) Photothermal Signal Peak Values (Unitized)
(2) Distance in the Y Direction (mm)

III. EXPERIMENTAL SET UP

For a schematic diagram of an experimental set up based on the concepts described above, see Fig.3. Polarized light emitted from a He-Ne laser with a power of 25mW passes through a $\lambda/2$ wave plate. In conjunction with this, it is modulated by wave chopper into a modulated light beam of frequency ω . Following this, it is focused by a lens on the side area of a right angle prism in order to couple it into a thin film wave guide. Thin film samples are pressed onto a right angle prism surface by a centering system. Changing the angle of incidence between incident light beams and prism surfaces, it is then possible, in thin films, to excite appropriate guided modes. Guided waves associated with these guided modes (that is, pump light) will propagate in thin films along the oz direction. Photothermal systems are set up on a guide. In the systems in question, survey probe laser beams (He-Ne laser) go through a lens vertically focused on sample thin film surfaces. As far as light beams penetrating the samples are concerned, their striations are checked by a quadrant detector. After the two mutually opposed quadrant output signals cancel each other out, they are imputed into a phase suppression amplifier. In conjunction with this, the operating frequency is selected as 13Hz. In order to check propagation attenuation associated with different thin film sample guided modes, photothermal monitoring systems--besides being able to follow wave guide coupling systems to make turning movements in order to guarantee, when in guided modes associated with different excitations, that survey probe light beams are always perpendicular to sample surfaces--are also capable, relative to thin film samples, of making accurate displacements in the oz and oY directions. The general steps in doing test measurements of guided wave propagation attenuation are: 1. Survey photothermal signals along directions perpendicular to guided wave light propagation (that is, photothermal signals associated with the OY direction, see

Fig.4a) 2. Move photothermal monitoring systems to measure photothermal signals associated with different propagation lengths (that is, different z value) Y directions. Selecting maximum values associated with photothermal signals in various Y directions, form a photothermal signal curve following z changes (Fig.4b) 3. On the basis of the definition of propagation attenuation: $I = I_0 e^{-\alpha z}$, use least square methods to draw up this photothermal signal curve, which characterizes guided wave light strength changes following along with propagation distances. It is then possible to fix propagation attenuation coefficient alpha.

This experimental set up is capable of realizing test measurements of guided wave propagation attenuation for 4dB/cm to 100dB/cm. Test measurement accuracy can reach 0.2dB/cm. Raising pump light energies, it is possible to expect to expand a step further measurement ranges.

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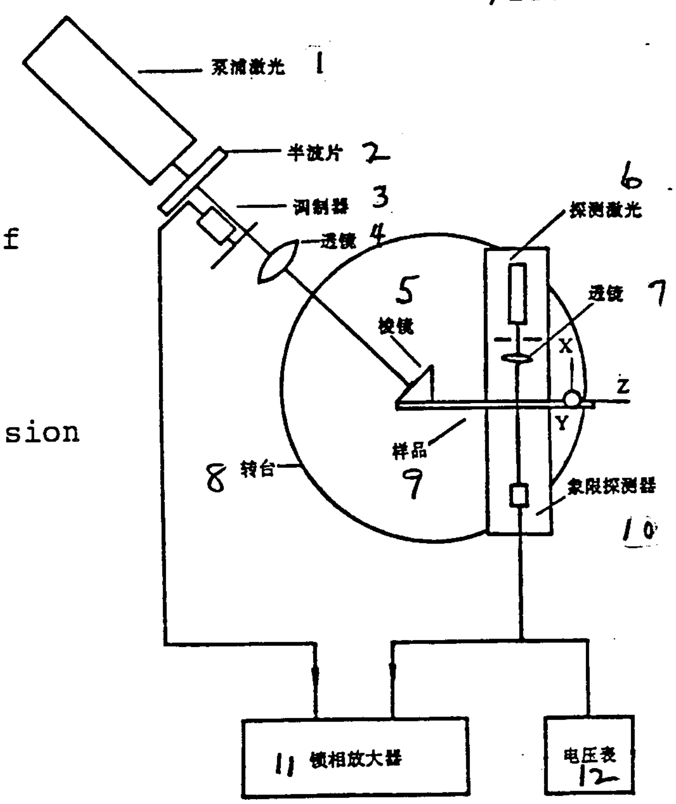

Fig.3 Experimental Equipment Schematic

Key: (1) Pump Laser (2) Half Wave Plate (3) Modulator (4) Lens (5) Prism (6) Survey Probe Laser (7) Lens (8) Turn Table (9) Sample (10) Quadrant Detector (11) Phase Suppression Amplifier (12) Voltmeter

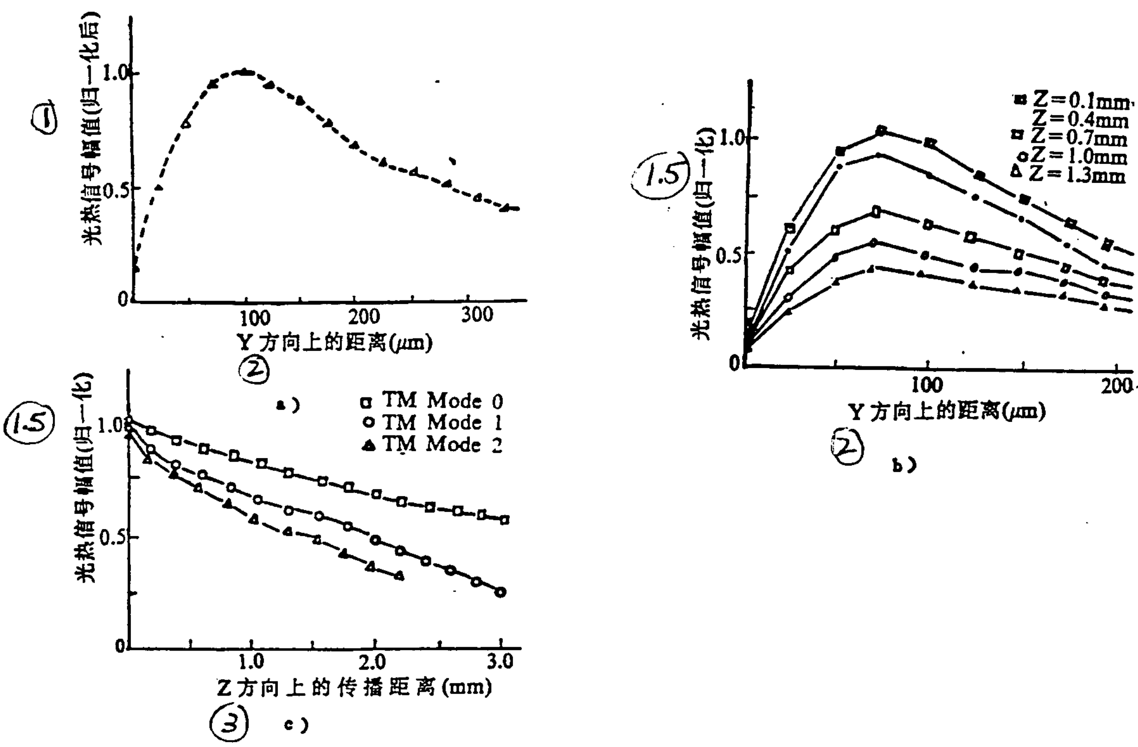

Fig.4

Key: (1) Photothermal Signal Peak Values (After Unitizing)
(1.5) Photothermal Signal Peak Values (Unitized)
(2) Y Direction Distance (3) Z Direction Propagation Distance
a) Photothermal Signals Associated with Guided Wave Light Cross Section Direction

b) Photothermal Signals Associated with Guided Wave Light at Different Propagation Distances Along the Y Direction

c) Changes in Photothermal Signals Along Direction of Propagation and Propagation Attenuation

IV. TEST MEASUREMENT ANALYSIS

Optical thin film sample losses have two parts--absorption and scattering losses. As far as high quality thin film samples are concerned, using the guided mode propagation attenuations in order to characterize thin film losses, it is possible to comprehensively represent the magnitudes of the two types of thin film absorption and scattering losses. Due to the fact that the range of guided wave light and thin film media actions is relatively large, the methods in question not only are very highly sensitive, but they are capable of completely reflecting thin film sample qualities--for example, thin film refraction index dulling coefficients, boundary surface micro roughness, and so on. Because of this, propagation attenuation is a comprehensive parameter characterizing thin film properties and quality.

Thin film samples are all Ta_2O_5 thin films plated by low pressure plasma reaction evaporation techniques. They possess high concentration densities and small losses as well as such advantages as strengths in keeping with substrates. Thin film structures and refractive indices are all very close to block materials. Traditional light intensity methods already have no way to reflect the losses. However, guided mode propagation attenuation is still capable of conveniently reflecting differences associated with losses in this type of sample [3]. Table 1 gives test measurement results for two pieces of thin film sample possessing the same optical thickness $6\lambda/4(\lambda=632.8nm)$ and 4 guided modes. Due to the fact that the structures of the two samples are the same, corresponding guided mode propagation angles are the same. In the table, results clearly show that: it goes without saying, there are TE modes and TM modes, lower order modes and higher order modes. Sample 1 propagation attenuations, in all cases, are larger than those of Sample 2. The explanation for this

is that the quality of Sample 1 is not as good as Sample 2. Its losses are greater than Sample 2.

TABLE 1. Ta_2O_5 THIN FILM SAMPLE PROPAGATION ATTENUATION TEST MEASUREMENT RESULTS* (dB/cm)

导模 (1)	样 品 1 (2)	样 品 2 (3)
TE0	23.5(±0.6)	9.1(±0.3)
TE1	35.6(±1.0)	14.6(±0.8)
TM0	21.9(±0.6)	11.4(±0.8)
TM1	38.9(±1.1)	17.9(±0.7)

* Data enclosed in parentheses represent the ranges of inaccuracy associated with measurements.

Key: (1) Guided Mode (2) Sample 1 (3) Sample 2

Guided mode propagation attenuation systems have very high sensitivities to defects in thin film media. It is possible to very sensitively reflect changes in losses given rise to by environmental changes. This type of change in losses is caused by tiny changes in thin film chemical or physical structure. Thin film drying technology is often used in the optimization and stabilizing of thin film optical characteristics. We did test measurements of the influence of drying on the losses of Ta_2O_5 thin films deposited by low pressure plasma reactions. This type of deposition technology causes Ta_2O_5 thin film structures to be compact. When dried in air at 200°C, the transmission rate and reflection rate optical spectrum curves lack clear changes. However, thin film guided mode propagation attenuation is still able to very sensitively reflect the influences of these drying techniques on losses. Table 2 gives propagation attenuation

TABLE 2 Unit: (dB/cm)

样 品 (1)	导模 (2)	烘 烤 前 (3)	烘 烤 后 (4)
样品A (6) (6λ/4)	TE0	52.4(±2.1)	20.9(±0.8)
	TE1	69.3(±2.7)	30.1(±1.2)
	TM0	57.8(±2.0)	22.8(±0.8)
	TM1	75.5(±3.1)	32.0(±1.6)
样品B (7) (12λ/4)	TE0	30.7(±0.9)	10.1(±0.2)
	TE1	30.5(±1.1)	12.0(±0.3)
	TE2	37.3(±1.5)	15.5(±0.6)
	TM0	30.0(±0.8)	10.0(±0.2)
	TM1	32.0(±1.4)	10.2(±0.4)
	TM2	40.8(±1.2)	14.0(±0.5)
	TM3	55.0(±2.1)	16.4(±0.7)

Key: (1) Sample (2) Guided Mode (3) Before Drying (4) After Drying (5) Unit (6) Sample A (7) Sample B

results for two Ta_2O_5 thin film samples with different /239
thicknesses before and after drying. After drying, the two sample propagation attenuations will be reduced close to 1/3 compared to before drying. It is possible to see that drying technique influences on thin film losses are capable of very adequate representation in propagation attenuation.

V. CONCLUSIONS

Using guided mode propagation attenuation coefficients possessed by thin film samples, it is possible to sensitively and fully reflect thin film sample loss characteristics, which is a help to high quality thin film sample analysis. Photothermal deflection techniques are capable of very sensitively measuring guided mode propagation attenuation. This type of measurement method possesses superiority with regard to those thin films or wave guide samples associated with relatively weak scattering losses. Besides this, this type of method--using photothermal deflection techniques to measure guided wave propagation attenuation--is not only capable of use in research on optical thin films. It is also completely capable of generalized application to measurements and analysis associated with

integrated optical planar wave guides as well as propagation attenuation in optical fibers.

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